A Look-up-table Approach to Inverting Remotely Sensed Ocean Color Data

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LONG-TERM GOAL

The overall goal of this work is to develop and evaluate a new spectrum-matching technique for rapidly inverting remotely sensed hyperspectral reflectances to recover environmental information such as water-column optical properties, bottom bathymetry, and bottom classification.

OBJECTIVES

We (led by lead PI C. Mobley, N0001400D01610001) are developing and evaluating a new technique for the extraction of environmental information including water-column inherent optical properties and shallow-water bathymetry and bottom classification from remotely-sensed hyperspectral ocean-color spectra. We address the need for rapid, automated interpretation of hyperspectral imagery. This year's work centered on streamlining the software for efficient image processing and analyzing the impacts of a much larger LUT data on the retrievals of bathymetry. The research issues focus on the development and evaluation of spectrum-matching algorithms, including quantification of how various types of errors in the measured spectrum influence the retrieved environmental data.

APPROACH

Our technique is based on a spectrum-matching and look-up-table (LUT) approach in which the measured remote-sensing reflectance spectrum is compared with a large database of spectra corresponding to known water, bottom, and external environmental conditions. The water and bottom conditions where the spectrum was measured are then taken to be the same as the conditions corresponding to the database spectrum that most closely match the measured spectrum. This technique was first developed and tested using Hydrolight-generated simulated. This year, we applied the LUT technique to Ocean PHILLS (Ocean Portable Hyperspectral Imager for Low-Light spectroscopy; Davis, et al., 2002) imagery taken during the ONR CoBOP (Coastal Benthic Optical Properties) field experiments at Lee Stocking Island (LSI), Bahamas and to imagery acquired near Looe Key, Florida in October 2002.

The Hydrolight radiative transfer numerical model (www.hydrolight.info; Mobley, 1994; Mobley and Sundman, 2001a,b) gives an exact solution of the radiative transfer equation given the inherent optical properties (IOPs, namely the absorption and scattering properties of the water body) of the water, the incident sky radiance, and the bottom depth and reflectance (bottom BRDF). The water IOPs can be

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14. ABSTRACT
The overall goal of this work is to develop and evaluate a new spectrum-matching technique for rapidly inverting remotely sensed hyperspectral reflectances to recover environmental information such as water-column optical properties, bottom bathymetry, and bottom classification.

15. SUBJECT TERMS

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built up from any number of components, such as various microbes, dissolved substances, organic detritus, mineral particles, or microbubbles. For remote-sensing purposes, the relevant Hydrolight output is the spectral water-leaving radiance or the remote-sensing reflectance.

The first step in the recovery of environmental information from a hyperspectral image is to construct a database containing remote-sensing reflectance spectra [$R_{rs}(\lambda)$, where λ is the wavelength] from a large number of Hydrolight runs corresponding to different combinations of water composition (different microbial, dissolved, or mineral substances at different concentrations), bottom conditions (sand, seagrass, coral, etc. at various depths), sky conditions (different solar angles and atmospheric conditions), sensor viewing directions, wavelengths, and so on. The resulting spectra in the database, $R_{rs}^{d}(\lambda)$, are all unique. Given a measured reflectance spectrum $R_{rs}^{m}(\lambda)$ (obtained after atmospheric correction of an at-sensor radiance), one can then "look up" the $R_{rs}^{d}(\lambda)$ spectrum that most closely matches $R_{rs}^{m}(\lambda)$ by some criterion such as a weighted least-squares minimization over wavelength. The water IOPs and bottom conditions in the actual water body are then taken to be the values that were used in Hydrolight to generate the selected $R_{rs}^{d}(\lambda)$. We thus effect an inversion of the measured spectral reflectance signature by the conceptually simple process of spectrum matching and then look up the answer in the database. It is important to note that we are working with calibrated R_{rs} spectra (units of sr^{-1}), not normalized or uncalibrated spectra. The use of calibrated spectra removes the non-uniqueness problems that arise with the use of normalized spectra.

WORK COMPLETED

In addition to the work described by the lead PI C. D. Mobley (N0001400D01610001), we performed other code development and numerical experiments that should be mentioned in the joint progress report.

The expansion of the LUT database to >200,000 entries increased the processing time of the Looe Key image from hours to weeks. Any further development of the LUT techniques require us to recode the spectrum matching code to more finely select appropriate spectrums to test against the measured R_{rs} spectra. This included better memory management, spectra magnitude threshold test, and more streamlined looping and table searching.

Once the streamlining was complete, we were able to begin bathymetric error analysis of the 12K vs. 200K LUT. The results were far different than expected and has forced us to address sensor and environmental noise (see Bissett N00014-04-1-0297) within the context of developing a more complete LUT approach.

RESULTS

The previous LUT table entries (11,000 total combinations of bathymetry, bottom type, and water column IOPs) were expanded to a total of 235,625 entries. In addition to the new bottom types and waters added to the LUT, the depth discretization was made finer. A detailed analysis of the sensor was done to find the discretization that was optimal for the current sensor and the applications; and it resulted in 145 optically unique depths (http://www.feriweb.org/Publications_ppts/2004_FERI_0003_U_D_LUT_Sen.pdf). As the LUT was made more diverse with added waters, bottoms, and a finer depth discretization, the inherent thought was that it will enhance the classification accuracy and that the derived bathymetry using the new LUT will have less average error per pixel then previous LUT did. To evaluate this, the Looe Key image, which had an average absolute error of 1.80 m in the depth derived with the old LUT as compared to SHOALS data, was classified using the new LUT.

Although, it was known that the time taken to classify the image would not be linear with the growth in the entries of LUT, the time taken to classify using the new LUT was operationally infeasible. At the rate that it was executing, it would have had taken about 15 days to classify just that one image. Thus, efforts were made to optimize the code for faster execution time. Bottlenecks that were responsible for slow execution were found in the code and were replaced with modified faster code. The resultant code took 6 hours to classify the image.

Contrary to the improvements expected using the new LUT, the derived bathymetry had a far worse average absolute error of 3.0 m. Some areas of the image had very low classification accuracy. The bathymetry derived from the new LUT in those areas were consistently less than the depth derived from SHOALS on an order of 8 to 10 meters (Figure 1).

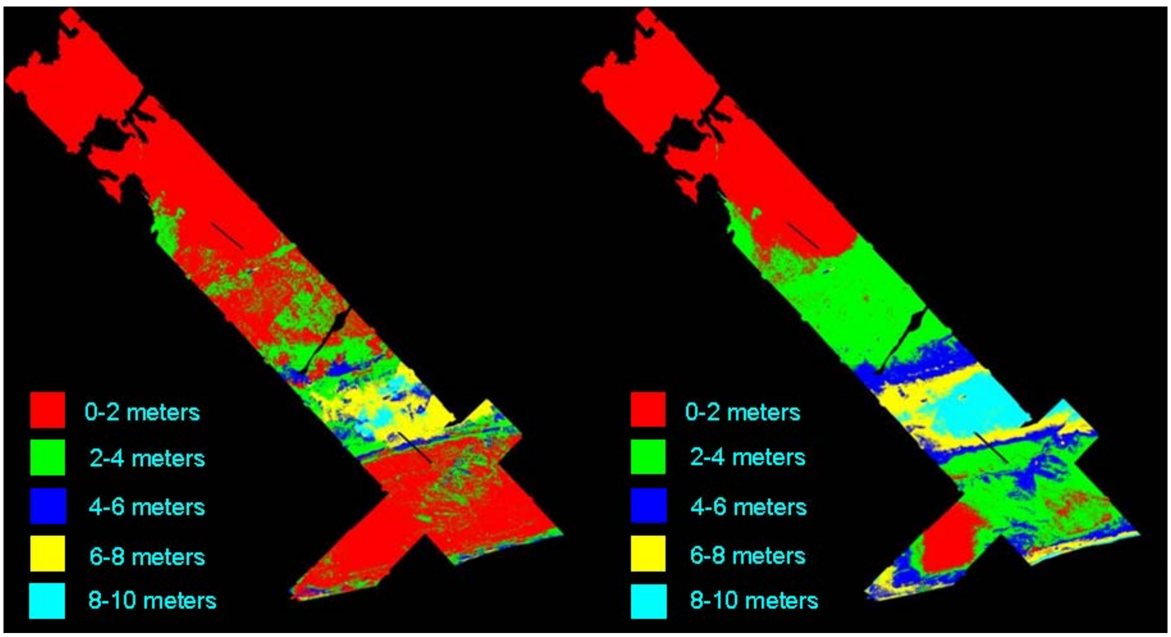

Figure 1. (LEFT) Absolute difference in depths derived from the old LUT and the SHOALS bathymetry. (RIGHT) Absolute difference in depths derived from the new LUT and the SHOALS bathymetry. Note the increase in bathymetric errors between the old 12K v. the new 200K LUT.

To investigate the source of misclassification, we selected two pixels from the areas show in Figure 2, and plotted them with the spectrums that were selected from the old and the new LUT (Figure 3 and 4). For the first pixel, the SHOALS derived depth is 14.6 m, the new LUT spectrum selected has a depth of 5.25 m and the old spectrum has a depth of 7 m (Figure 3). The second pixel has the SHOALS derived depth of 7.16 m, the new LUT derived depth of 4.5 m, and the old LUT derived depth of 6.5 m (Figure 4). It was clear that while the database spectrum was better matched to the image spectrum, the retrieve bathymetry was in greater error. Looking further at the spectra in plot 1 of Figure 2, we sought to analyze was how good all the database spectrum with the depth of 14.6 meters fitted the image spectrum. Figure 5 has the image spectrum plotted with all the LUT spectrums with depth of 14.6 meters (Plot 1 of Figure 2).

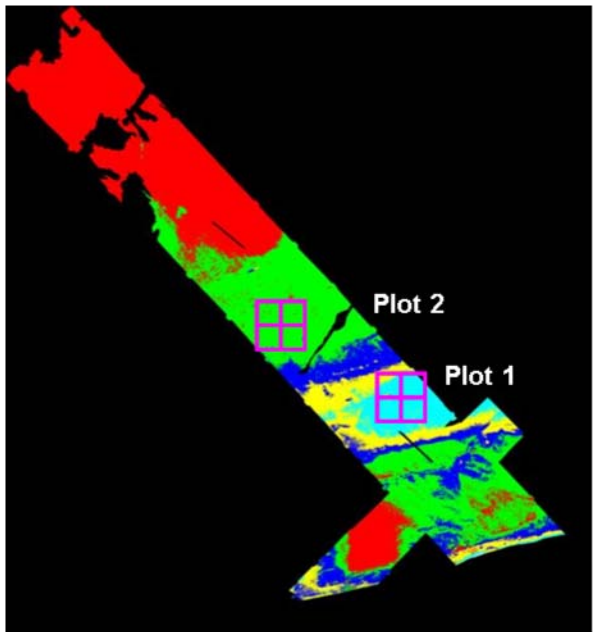

Figure 2. Location of Rrs spectra for further analysis of 12K v. 200K LUT differences.

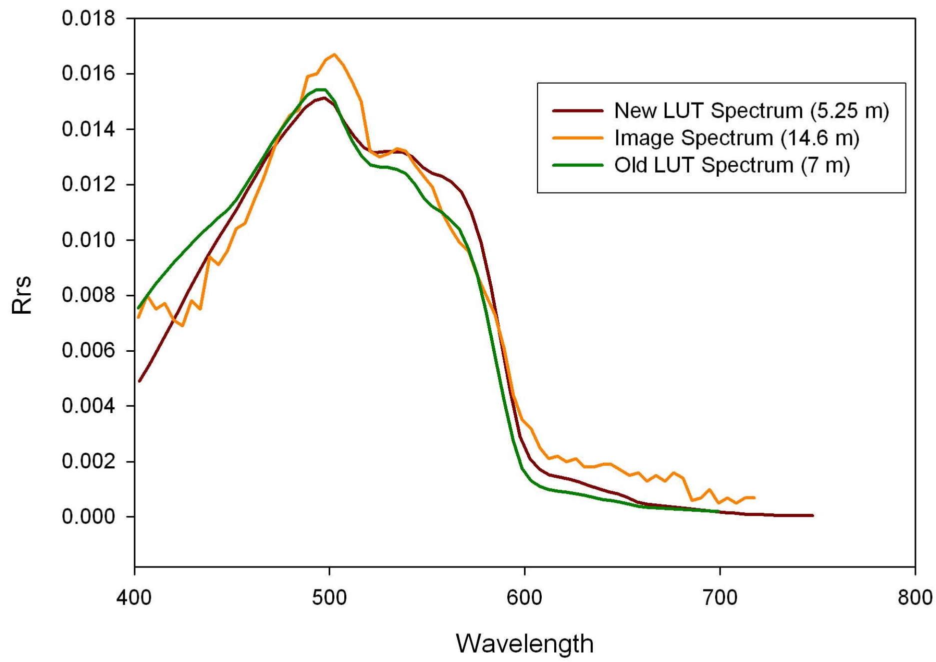

Figure 3. Image spectrum and the selected LUT spectrums from plot position 1 in Figure 2. Note the note that the new LUT spectrum matches the Rrs spectra better than the old LUT. However, the new LUT has a greater bathymetric error.

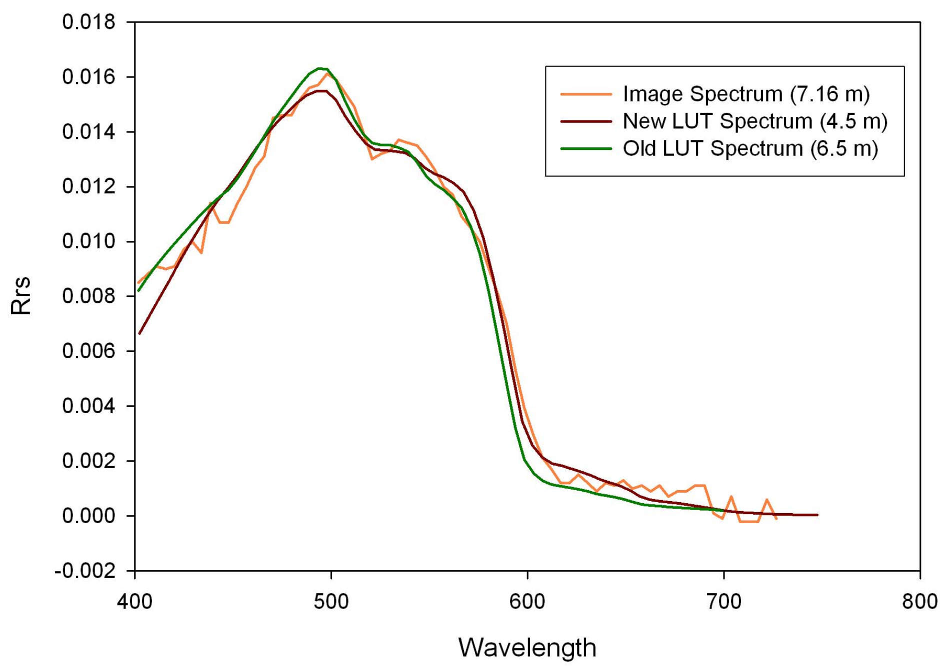

Figure 4. Image spectrum and the selected LUT spectrums from plot position 1 in Figure 2. Note the note that the new LUT spectrum matches the Rrs spectra better than the old LUT. However, the new LUT has a greater bathymetric error.

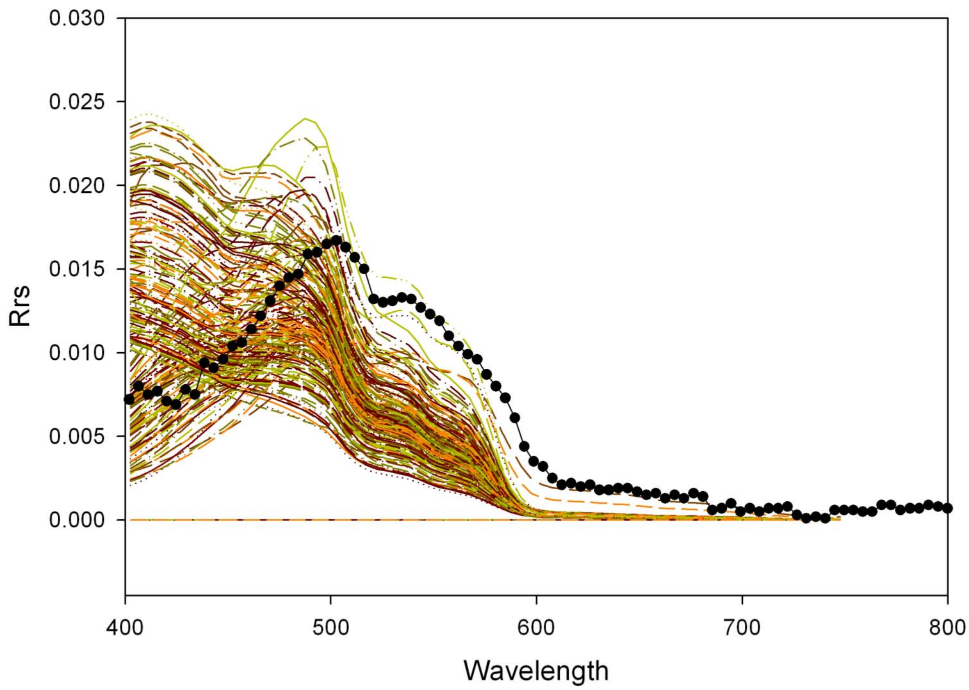

Figure 5. The image Rrs spectrum from plot 1 in Figure 2 (black line) is plotted with all the 14.6 meter LUT spectrums. Thresholding was done to minimize the number of spectrum in plot to maintain readability.

Two things are evident from these graphs. The first is that it is possible that the larger database may actually produce greater errors through noise in the Rrs spectrum (Figure 3 and 4), resulting from either sensor or environmental noise components. The second thing evident is that while the depth discretization may produce a finer resolution in the vertical resolution, if the IOPs or the bottom reflectance actually found in the image space are not represented in the LUT database, the depth errors may still be significant (Figure 6).

These results are leading us to develop new methodologies in searching the LUT database, as well as the establishment of confidence indicators to better determine the suitability of a spectrum match. This will be the focus of the FY 2006 projects.

IMPACT/APPLICATION

The problem of extracting environmental information from remotely sensed ocean color spectra is fundamental to a wide range of basic and applied science problems. Extraction of bathymetry and bottom classification is especially valuable for planning military operations in denied access areas. No single inversion technique can be expected to be superior in all situations; therefore all techniques must be evaluated. In addition to investigating a new type of inversion, part of our work is to evaluate when the LUT technique is superior to other techniques, and when it is not. This work thus adds to the existing suite of remote sensing analysis techniques.

TRANSITIONS

Various databases of water IOPs, bottom reflectances, and the corresponding R_{rs} spectra, along with the specialized Hydrolight code and spectrum-matching algorithms have been transitioned to the Naval Research Laboratory (Remote Sensing Division) for processing PHILLS and PHILLS-2 imagery.

RELATED PROJECTS

This work is being conducted in conjunction Curt Mobley, N0001404C0218, and another ONR program funded to the PI, N00014-04-1-0297)

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Mobley, C. D., L. K. Sundman, C. O. Davis, T. V. Downes, R. A. Leathers, M. J. Montes, J. H. Bowles, W. P. Bissett, D. D. R. Kohler, R. P. Reid, E. M. Louchard, and A. Gleason, 2005. Interpretation of hyperspectral remote-sensing imagery via spectrum matching and look-up tables. *Applied Optics* **44**(17), 3576-3592. [published, refereed]

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